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Graphene may help to solve the Casimir conundrum in indium tin oxide systems

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Abstract

© 2018 American Physical Society. We reconsider the long-explored problem that the magnitude of the measured Casimir force between an Au sphere and an indium tin oxide (ITO) film decreases significantly after the UV treatment with no respective changes in the ITO dielectric permittivity required by the Lifshitz theory. Two plausible resolutions of this conundrum are discussed: the phase transition of an ITO film from metallic to dielectric state and the modification of a film surface under the action of UV light. To exclude the latter option, we propose an improvement in the experimental scheme by adding a graphene sheet on top of an ITO film. The formalism is developed allowing precise calculation of the Casimir force between an Au sphere and a graphene sheet on top of ITO film deposited on a quartz substrate. In doing so Au, ITO, and quartz are described by the frequency-dependent dielectric permittivities and real graphene sheet with nonzero mass-gap parameter and chemical potential by the polarization tensor at nonzero temperature. Numerical computations performed both before and after the phase transition resulting from the UV treatment show that the presence of graphene leads to only a minor decrease in the drop of the Casimir force which remains quite measurable. At the same time, in the presence of graphene the guess that an observed drop originates from the modification of an ITO surface by the UV light breaks down. Similar results are obtained for the configuration of two parallel plates consisting of a graphene sheet, an ITO film, and a quartz substrate. The proposed experiments involving additional graphene sheets may help in resolution of the problems arising in application of the Lifshitz theory to real materials.

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References

[1] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and F. Capasso, Quantum mechanical actuation of microelectromechanical system by the Casimir effect, Science 291, 1941 (2001). SCIEAS 0036-8075 10.1126/science.1057984

[2] H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, and F. Capasso, Nonlinear Micromechanical Casimir Oscillator, Phys. Rev. Lett. 87, 211801 (2001). PRLTAO 0031-9007 10.1103/PhysRevLett.87.211801

[3] J. Barcenas, L. Reyes, and R. Esquivel-Sirvent, Scaling of micro- and nanodevices actuated by the Casimir force, Appl. Phys. Lett. 87, 263106 (2005). APPLAB 0003-6951 10.1063/1.2152835

[4] R. Esquivel-Sirvent and R. Pérez-Pascual, Geometry and charge carrier induced stability in Casimir actuated nanodevices, Eur. Phys. J. B 86, 467 (2013). EPJBFY 1434-6028 10.1140/epjb/e2013-40779-5

[5] W. Broer, G. Palasantzas, J. Knoester, and V. B. Svetovoy, Significance of the Casimir force and surface roughness for actuation dynamics of MEMS, Phys. Rev. B 87, 125413 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.125413

[6] W. Broer, H. Waalkens, V. B. Svetovoy, J. Knoester, and G. Palasantzas, Nonlinear Actuation Dynamics of Driven Casimir Oscillators with Rough Surfaces, Phys. Rev. Applied 4, 054016 (2015). 2331-7019 10.1103/PhysRevApplied.4.054016

[7] M. Sedighi, W. Broer, G. Palasantzas, and B. J. Kooi, Sensitivity of micromechanical actuation on amorphous to crystalline phase transformations under the influence of Casimir forces, Phys. Rev. B 88, 165423 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.88.165423

[8] J. Zou, Z. Marcet, A. W. Rodriguez, M. T. H. Reid, A. P. McCauley, I. I. Kravchenko, T. Lu, Y. Bao, S. G. Johnson, and H. B. Chan, Casimir forces on a silicon micromechanical chip, Nat. Commun. 4, 1845 (2013). 2041-1723 10.1038/ncomms2842

[9] L. Tang, M. Wang, C. Y. Ng, M. Nicolic, C. T. Chan, A. W. Rodriguez, and H. B. Chan, Measurement of non-monotonic Casimir forces between silicon nanostructures, Nat. Photon. 11, 97 (2017). 1749-4885 10.1038/nphoton.2016.254

[10] N. Inui, Optical switching of a graphene mechanical switch using the Casimir effect, J. Appl. Phys. 122, 104501 (2017). JAPIAU 0021-8979 10.1063/1.4993672

[11] G. L. Klimchitskaya, V. M. Mostepanenko, V. M. Petrov, and T. Tschudi, Optical Chopper Driven by the Casimir Force, Phys. Rev. Applied 10, 014010 (2018). 2331-7019 10.1103/PhysRevApplied.10.014010

[12] E. M. Lifshitz and L. P. Pitaevskii, Statistical Physics, Pt. II (Pergamon Press, Oxford, 1984).

[13] M. Bordag, G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, Advances in the Casimir Effect (Oxford University Press, Oxford, 2015).

[14] H. L. Hartnagel, A. L. Dawar, A. K. Jain, and C. Jagadish, Semiconducting Transparent Thin Films (Institute of Physics Publishing, Bristol, 1995).

[15] S. de Man, K. Heeck, R. J. Wijngaarden, and D. Iannuzzi, Halving the Casimir Force with Condictive Oxides, Phys. Rev. Lett. 103, 040402 (2009). PRLTAO 0031-9007 10.1103/PhysRevLett.103.040402

[16] S. de Man, K. Heeck and D. Iannuzzi, Halving the Casimir force with condictive oxides: Experimental details, Phys. Rev. A 82, 062512 (2010). PLRAAN 1050-2947 10.1103/PhysRevA.82.062512

[17] C.-C. Chang, A. A. Banishev, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Reduction of the Casimir Force from Indium Tin Oxide Film by UV Treatment, Phys. Rev. Lett. 107, 090403 (2011). PRLTAO 0031-9007 10.1103/PhysRevLett.107.090403

[18] A. A. Banishev, C.-C. Chang, R. Castillo-Garza, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Modifying the Casimir force between indium tin oxide plate and Au sphere, Phys. Rev. B 85, 045436 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.85.045436

[19] F. Chen, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Demonstration of optically modulated dispersion forces, Opt. Express 15, 4823 (2007). OPEXFF 1094-4087 10.1364/OE.15.004823

[20] F. Chen, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Control of the Casimir force by the modification of dielectric properties with light, Phys. Rev. B 76, 035338 (2007). PRBMDO 1098-0121 10.1103/PhysRevB.76.035338

[21] J. M. Obrecht, R. J. Wild, M. Antezza, L. P. Pitaevskii, S. Stringari, and E. A. Cornell, Measurement of the Temperature Dependence of the Casimir-Polder Force, Phys. Rev. Lett. 98, 063201 (2007). PRLTAO 0031-9007 10.1103/PhysRevLett.98.063201

[22] G. L. Klimchitskaya and V. M. Mostepanenko, Conductivity of dielectric and thermal atom-wall interaction, J. Phys. A: Math. Theor. 41, 312002 (2008). 1751-8113 10.1088/1751-8113/41/31/312002

[23] B. Geyer, G. L. Klimchitskaya, and V. M. Mostepanenko, Thermal quantum field theory and the Casimir interaction between dielectrics, Phys. Rev. D 72, 085009 (2005). PRVDAQ 1550-7998 10.1103/PhysRevD.72.085009

[24] B. Geyer, G. L. Klimchitskaya, and V. M. Mostepanenko, Analytic approach to the thermal Casimir force between metal and dielectric, Ann. Phys. (NY) 323, 291 (2008). APNYA6 0003-4916 10.1016/j.aop.2007.04.005

[25] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, Casimir-Polder force between an atom and a dielectric plate: Thermodynamics and experiment, J. Phys. A: Math. Theor. 41, 432001 (2008). 1751-8113 10.1088/1751-8113/41/43/432001

[26] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, The Casimir force between real materials: Experiment and theory, Rev. Mod. Phys. 81, 1827 (2009). RMPHAT 0034-6861 10.1103/RevModPhys.81.1827

[27] C. N. Li, A. B. Djurišić, C. Y. Kwong, P. T. Lai, W. K. Chan, and S. Y. Liu, Indium tin oxide surface treatments for improvement of organic light-emitting diode performance, Appl. Phys. A 80, 301 (2005). APAMFC 0947-8396 10.1007/s00339-003-2146-0

[28] J. R. Vig, UV/ozone cleaning of surfaces, J. Vac. Sci. Technol. A 3, 1027 (1985). JVTAD6 0734-2101 10.1116/1.573115

[29] J. Xu, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Reducing detrimental electrostatic effect in Casimir-force measurements and Casimir-force-based microdevices, Phys. Rev. A 97, 032501 (2018). 2469-9926 10.1103/PhysRevA.97.032501

[30] G. Gómez-Santos, Thermal van der Waals interaction between graphene layers, Phys. Rev. B 80, 245424 (2009). PRBMDO 1098-0121 10.1103/PhysRevB.80.245424

[31] D. Drosdoff and L. M. Woods, Casimir forces and graphene sheets, Phys. Rev. B 82, 155459 (2010). PRBMDO 1098-0121 10.1103/PhysRevB.82.155459

[32] Bo E. Sernelius, Retarded interactions in graphene systems, Phys. Rev. B 85, 195427 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.85.195427

[33] A. D. Phan, N. A. Viet, N. A. Poklonski, L. M. Woods, and C. H. Le, Interaction of a graphene sheet with a ferromagnetic metal plate, Phys. Rev. B 86, 155419 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.86.155419

[34] N. Knusnutdinov, R. Kashapov, and L. M. Woods, Casimir-Polder effect for a stack of conductive planes, Phys. Rev. A 94, 012513 (2016). 2469-9926 10.1103/PhysRevA.94.012513

[35] I. V. Fialkovsky, V. N. Marachevsky, and D. V. Vassilevich, Finite-temperature Casimir effect for graphene, Phys. Rev. B 84, 035446 (2011). PRBMDO 1098-0121 10.1103/PhysRevB.84.035446

[36] M. Bordag, G. L. Klimchitskaya, and V. M. Mostepanenko, Thermal Casimir effect in the interaction of graphene with dielectrics and metals, Phys. Rev. B 86, 165429 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.86.165429

[37] M. Chaichian, G. L. Klimchitskaya, V. M. Mostepanenko, and A. Tureanu, Thermal Casimir-Polder interaction of different atoms with graphene, Phys. Rev. A 86, 012515 (2012). PLRAAN 1050-2947 10.1103/PhysRevA.86.012515

[38] G. L. Klimchitskaya and V. M. Mostepanenko, Van der Waals and Casimir interactions between two graphene sheets, Phys. Rev. B 87, 075439 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.075439

[39] M. Bordag, G. L. Klimchitskaya, V. M. Mostepanenko, and V. M. Petrov, Quantum field theoretical description for the reflectivity of graphene, Phys. Rev. D 91, 045037 (2015) PRVDAQ 1550-7998 10.1103/PhysRevD.91.045037;

[40] M. Bordag, G. L. Klimchitskaya, V. M. Mostepanenko, and V. M. Petrov, Quantum field theoretical description for the reflectivity of graphene, Phys. Rev. D 93, 089907 (E) (2016). 2470-0010 10.1103/PhysRevD.93.089907

[41] G. L. Klimchitskaya and V. M. Mostepanenko, Origin of large thermal effect in the Casimir interaction between two graphene sheets, Phys. Rev. B 91, 174501 (2015). PRBMDO 1098-0121 10.1103/PhysRevB.91.174501

[42] M. Bordag, I. Fialkovskiy, and D. Vassilevich, Enhanced Casimir effect for doped graphene, Phys. Rev. B 93, 075414 (2016) 2469-9950 10.1103/PhysRevB.93.075414;

[43] M. Bordag, I. Fialkovskiy, and D. Vassilevich, Enhanced Casimir effect for doped graphene, Phys. Rev. B 95, 119905 (E) (2017). 2469-9950 10.1103/PhysRevB.95.119905

[44] G. Bimonte, G. L. Klimchitskaya, and V. M. Mostepanenko, Thermal effect in the Casimir force for graphene and graphene-coated substrates: Impact of nonzero mass gap and chemical potential, Phys. Rev. B 96, 115430 (2017). 2469-9950 10.1103/PhysRevB.96.115430

[45] C. Henkel, G. L. Klimchitskaya, and V. M. Mostepanenko, Influence of chemical potential on the Casimir-Polder interaction between an atom and gapped graphene or graphene-coated substrate, Phys. Rev. A 97, 032504 (2018). 2469-9926 10.1103/PhysRevA.97.032504

[46] G. L. Klimchitskaya, U. Mohideen, and V. M. Mostepanenko, Theory of the Casimir interaction for graphene-coated substrates using the polarization tensor and comparison with experiment, Phys. Rev. B 89, 115419 (2014). PRBMDO 1098-0121 10.1103/PhysRevB.89.115419

[47] A. A. Banishev, H. Wen, J. Xu, R. K. Kawakami, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Measuring the Casimir force gradient from graphene on a (Equation presented) substrate, Phys. Rev. B 87, 205433 (2013). PRBMDO 1098-0121 10.1103/PhysRevB.87.205433

[48] G. L. Klimchitskaya and V. M. Mostepanenko, Reflectivity properties of graphene with nonzero mass-gap parameter, Phys. Rev. A 93, 052106 (2016). 2469-9926 10.1103/PhysRevA.93.052106

[49] G. Bimonte, T. Emig, R. L. Jaffe, and M. Kardar, Casimir forces beyond the proximity force approximation, Europhys. Lett. 97, 50001 (2012). EULEEJ 0295-5075 10.1209/0295-5075/97/50001

[50] G. Bimonte, T. Emig, and M. Kardar, Material dependence of Casimir forces: Gradient expansion beyond proximity, Appl. Phys. Lett. 100, 074110 (2012). APPLAB 0003-6951 10.1063/1.3686903

[51] L. P. Teo, Material dependence of Casimir interaction between a sphere and a plate: First analytic correction beyond proximity force approximation, Phys. Rev. D 88, 045019 (2013). PRVDAQ 1550-7998 10.1103/PhysRevD.88.045019

[52] G. Bimonte, Going beyond PFA: A precise formula for sphere-plate Casimir force, Europhys. Lett. 118, 20002 (2017). EULEEJ 0295-5075 10.1209/0295-5075/118/20002

[53] A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, The electronic properties of graphene, Rev. Mod. Phys. 81, 109 (2009). RMPHAT 0034-6861 10.1103/RevModPhys.81.109

[54] P. K. Pyatkovsky, Dynamical polarization, screening, and plasmons in gapped graphene, J. Phys.: Condens. Matter 21, 025506 (2009). JCOMEL 0953-8984 10.1088/0953-8984/21/2/025506

[55] V. P. Gusynin, S. G. Sharapov, and J. P. Carbotte, On the universal ac optical background in graphene, New J. Phys. B 11, 095013 (2009). NJOPFM 1367-2630 10.1088/1367-2630/11/9/095013

[56] L. A. Falkovsky, Optical properties of graphene, J. Phys.: Conf. Series 129, 012004 (2008). 1742-6596 10.1088/1742-6596/129/1/012004

[57] Handbook of Optical Constants of Solids, edited by E. D. Palik (Academic, New York, 1985).

[58] L. Bergström, Hamaker constants of inorganic materials, Adv. Colloid Interface Sci. 70, 125 (1997). ACISB9 0001-8686 10.1016/S0001-8686(97)00003-1

[59] C.-C. Chang, A. A. Banishev, R. Castillo-Garza, G. L. Klimchitskaya, V. M. Mostepanenko, and U. Mohideen, Gradient of the Casimir force between Au surfaces of a sphere and a plate measured using an atomic force microscope in a frequency-shift technique, Phys. Rev. B 85, 165443 (2012). PRBMDO 1098-0121 10.1103/PhysRevB.85.165443